

Galaxy Dynamics: from the Early Universe to the Present
ASP Conference Series, Vol. 3 × 10⁸, 1999
F. Combes, G. A. Mamon and V. Charmandaris, eds.

Bar-driven Galaxy Evolution and Time-scales to Feed AGN

F. Combes

*DEMIRM, Observatoire de Paris, 61 Av. de l'Observatoire, F-75 014,
 Paris, France*

Abstract. Recent progress in the understanding of the role of bars and gravitational instabilities in galaxy disks is reviewed. It has been proposed that bars can produce mass transfer towards the center, and progressively metamorphose late-type galaxies in early-types, along the Hubble sequence. Through this mass transfer, bars are self-destroyed, and can act only during a certain "duty-cycle" in the galaxy life. After sufficient gas infall, another bar-phase can spontaneously occur. This recurrent evolution is strongly dependent on environment. A scenario is proposed, based on N-body simulations time-scales of the bar-life events, to explain the observed bar frequency, gas mass fraction, bulge and possible black hole mass growth, in a typical spiral.

1. Formation and Evolution of Bars

Bars as dynamical phenomena are much more understood than 20 years ago. In the 70s, the first numerical simulations carried out in the aim to find spiral structure, have established instead that bars are ubiquitous (Miller et al. 1970, Hohl 1971, Hockney & Brownrigg 1974). Since then, numerous N-body simulations, considering only the stellar component, have confirmed that bars are robust, and stay for a Hubble time (Sellwood 1981, Combes & Sanders 1981). But, as we shall see in this review, this is no longer true when gas is taken into account!

Bars can be considered as long-lived modes, as superposition of leading and trailing waves (or a standing wave). They grow through swing amplification (e.g. Toomre 1981). Waves can be reflected at the center, at corotation, but might be damped at the inner Lindblad resonance (at least in the linear regime). In N-body simulations, the pattern speed takes first high values, larger than the peak of the $\Omega - \kappa/2$ curve, then the bar slows down, and there exists one or two ILRs.

The bar instability begins in the center, where the precession speed of elliptical-like orbits, $\Omega - \kappa/2$, is high. Then, the bar traps more and more particles, which slows it down; indeed, the particles farther from the center precess more slowly. Angular momentum is taken away by the spiral, which amplifies the bar (Sellwood & Wilkinson 1993, Pfenniger & Friedli 1991).

After their formation, bars can be further slowed down by dynamical friction against a dark matter halo, if it is concentrated enough (Debattista & Sellwood 1998). The fact that bars are not observed with low pattern speeds seem to

imply that the dark matter fraction inside the bar radius is negligible, or that the dark matter is rotating fast (Tremaine & Ostriker 1999).

The existence of inner Lindblad resonances is confirmed in many barred spiral observations: rings and characteristic resonant features are observed at ILRs (Buta & Combes 1996). Also the gas behavior, traced by dust lanes, shocks etc., have confirmed the predictions of simulations (Athanasoulas 1992).

2. Gas Instabilities, Regulation and Feedback

The presence of gas changes considerably the picture. Dissipation and star formation are essential phenomena. The stellar component is heated by the spiral waves and gravitational instabilities, and after the bar is established, the system is then stable, in absence of gas. Torques are exerted on the stars by the spiral wave (since the potential and density extrema are not in phase), but this is no longer the case for a bar, by symmetry. A lenticular galaxy without gas can stay barred for more than a Hubble time.

On the contrary, gas is continuously cooled, and spiral instabilities are renewed, that influence the stellar component, too (Friedli & Benz 1993, Heller & Shlosman 1996). Gravity torques from the bar to the disk matter are therefore maintained, and no equilibrium is possible. Since torques are continuously present, one can apply the theory of “viscous disks”: angular-momentum is transferred outwards, to a small fraction of matter that escapes to infinity, while the bulk of the disk mass is driven inwards. If the “viscous” time to redistribute angular momentum t_{vis} is of the same order as the time scale to form stars t_* , then an exponential disk of stars is created (Lin & Pringle 1987a).

The radial redistribution of matter is done by gravity torques. The viscosity here is therefore not the normal gas viscosity (which anyhow is not efficient in the interstellar medium at galactic scales), but the gravitational viscosity (Lin & Pringle 1987b). Gravitational instabilities are suppressed at small scales by random motions, and the corresponding “pressure” through the local velocity dispersion c , and at large scale by rotation. The corresponding stability intervals are overlapping if $Q = c\kappa/(\pi G\mu) = c/c_{crit} > 1$, where μ is the disk surface density (Toomre 1964). The evolution of the disk is then controlled by recurrent waves, through a regulating mechanism, and feedback processes:

- 1) at a given epoch, the disk is cold ($Q < 1$), and therefore unstable to spiral and bar waves
- 2) the disk then develops waves, non-axisymmetry and gravity torques, that transfer the angular momentum outwards (through trailing waves). The waves heat the disk, until Q is 1.
- 3) then a disk with only a stellar component will remain stable, while a gaseous disk can cool back to step 1.

The size of the region over which angular momentum is transferred is $\lambda_c \propto G\mu/\Omega^2$, and the corresponding time-scale is $2\pi/\Omega$; the effective kinematic viscosity is $\nu \sim \lambda_c^2\Omega$ and the viscous time can be estimated as $t_{vis} \sim r^2/\nu \sim r^2\Omega^3/(G^2\mu^2)$. Now, there might be approximate agreement between the two time-scales, viscosity and star-formation, since the two processes depend exactly on the same gravitational instabilities. Empirically, Q appears to control star-formation in spiral disks (Kennicutt 1989). Then $t_{vis} \sim t_*$, which could be

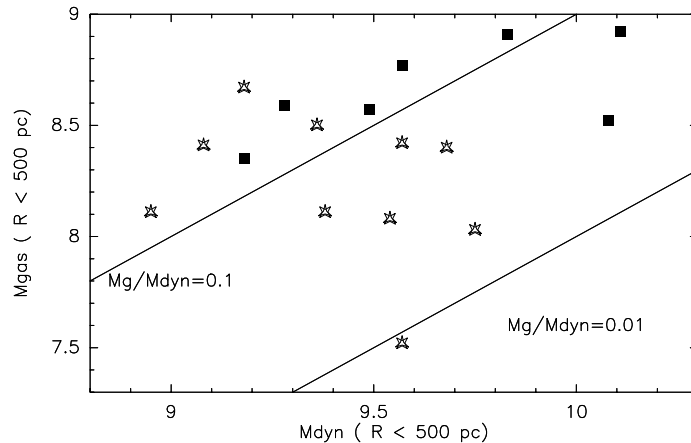


Figure 1. Molecular gas and dynamical masses inside 500pc for barred galaxies (filled squares) and non-barred galaxies (stars), from Sakamoto et al. (1999)

the origin of the exponential light distribution of the disk, and its exponential metallicity gradient. The time-scale for bar-driven evolution is of the order of a few dynamical time-scales. The controlling time-scale is that of gas accretion, and depends strongly on the environment.

That radial gas flows are efficient in barred galaxies is supported by observations; barred galaxies have more H_2 gas concentration inside their central 500pc than un-barred galaxies (cf fig. 1, Sakamoto et al 1999). Also, the radial flows level out abundance gradients in barred galaxies (Martin & Roy 1994).

3. Death of Bars and AGN Fueling

3.1. Central Concentrations

The inflow of matter in the center can destroy the bar. It is sufficient that 5% of the mass of the disk has sunk inside the inner Lindblad resonance (Hasan & Norman 1990, Pfenniger & Norman 1990, Hasan et al 1993). But this depends on the mass distribution, on the size of the central concentration; a point mass like a black hole is more efficient (maybe 2% is sufficient). The destruction is due to the mass re-organisation, that perturbs all the orbital structure: the x_1 orbits sustaining the bar for instance are shifted outwards. Near the center, the central mass axisymmetrizes the potential. Then there is a chaotic region, and outside a regular one again. When a central mass concentration exists initially, in N-body simulations, a bar still forms, but dissolves more quickly. It is also possible that after a bar has dissolved, another one forms, after sufficient gas accretion to generate new gravitational instabilities: the location of the resonances will not be the same.

If the radial inflow of gas is not violent, but slow enough, the bar is weakened but not completely destroyed. The process begins by the formation of two ILRs, through the mass concentration. Since the periodic orbits inside the two ILRs are perpendicular to the bars, this weakens the bar, and the mass flow is halted. The process is self-regulating (Combes 1996; Sellwood & Moore 1999).

A long term evolution of the bar is the box-peanut formation. The stellar bar thickens through vertical resonances, in a Gyr time-scale (Combes et al 1990, Raha et al. 1991). This does not destroy the bar. But if the bar is destroyed afterwards by a central mass concentration, then this is a way to form bulges. The observed correlation between scale-lengths of bulges and disks supports this mechanism (Courteau et al 1996). Bars appear to exist in most box-peanut shape galaxies (Merrifield & Kuijken 1995, Bureau & Freeman 1997).

3.2. Fueling the Nucleus

If the mass concentration is not sufficiently large, the gravity torques accumulate the gas in a nuclear ring at ILR. The curve $\Omega - \kappa/2$ (precession rate of elongated orbits in the epicyclic approximation) is an increasing function of radius inside ILR. On losing energy due to collisions and dissipation, the gas inflows, and precesses then more slowly: it trails with respect to the pattern. It experiences then positive gravity torques, and acquires angular momentum. It is therefore piling up back into the ring.

If there exists a sufficient mass concentration (massive black hole), the sense of variation of $\Omega - \kappa/2$ is reversed, the gas leads, might form a leading spiral structure, and experiences negative torques from the bar. The gas is driven further in, and can fuel the nucleus. Fueling is possible, once a sufficiently massive black hole is formed (Fukuda et al 1998).

3.3. Bars within Bars

When the mass accumulation grows in the center, $\Omega - \kappa/2$ is increasing rapidly, and 2 ILRs are created with perpendicular x^2 orbits. Time-scales are therefore two different between the center and outer parts, this forces the decoupling of a nuclear pattern from the large-scale bar (Friedli & Martinet 1993, Combes 1994). Nuclear disks are frequently observed, kinematically as well (cf HST nuclear spirals, Barth et al 1995; mm interferometers, Ishizuki et al 1990).

The second bars rotate with a much faster angular velocity. To avoid chaos, the two bars have a resonance in common. It is frequent that the ILR of the primary coincides with the corotation of the secondary. Multiply periodic particle orbits have been identified in such time-varying potentials (Maciejewski & Sparke 1998). It is possible that the two bars exchange energy with each other, through non-linear coupling; then $m = 4$ and $m = 0$ modes are also expected, and these have been seen in simulations (Masset & Tagger 1998). Even then, the life-time of the ensemble is rather short, a few rotations. But the nuclear bars could help to prolonge the action of the primary bar towards the nucleus (as first proposed by Shlosman et al. 1989).

Other mechanisms are possible to help to fuel gas into the nucleus; when the central nuclear disk becomes gas-dominated, it is so unstable that clumps are formed, creating a lot of non-axisymmetry (Heller & Shlosman 1994). Eventually, dynamical friction of giant molecular clouds on the bulge, is very efficient,

as soon as the clouds are inside a couple hundred parsecs ($t_{fric} \propto r^2$ and is 3×10^7 yr at $r=200$ pc for a GMC of $10^7 M_\odot$).

3.4. Observational Tests of Bar-driven Fueling

Observations have shown that dynamical perturbations (bars or tides) are efficient to trigger nuclear starbursts (Kennicutt et al 1987, Sanders et al 1988). Besides, there are frequent associations between nuclear starbursts and AGN activity (Mirabel et al 1992). Gas flow is the necessary condition to nuclear activity and AGN-FRII (radio jets) are interacting (Heckman et al 1986, Baum et al 1992), as well as QSOs (Hutchings & Neff 1992, Hutching & Morris 1995).

But evidences for the correlation of bars and activity has been difficult to obtain and controversial up to now. The correlation is found in some samples (Dahari 1984, Simkin et al 1980, Moles et al 1995), while no more bars or interactions have been found for Seyfert galaxies studied in the near-infrared (McLeod & Rieke 1995, Regan & Mulchaey 1999).

The case of Low Surface Brightness galaxies (LSB) is also a puzzle. LSB are unevolved objects, in isolated environments, with no mass concentrations. However 2/8 of them have Seyfert nuclei (instead of 1% expected, Sprayberry et al 1995). The probability of this configuration is only 2×10^{-6} . Further work should be done here, to eliminate all selection effects.

The lack of clear and obvious correlations between bars and AGN might not be surprising, in view of the self-destruction process described earlier: nuclear activity requires gas flows, that are sufficient to destroy the bar. An anti-correlation could even be expected, according to the chronology and time-scales.

4. Schematic Evolution Scenario

Now that bar evolution is relatively well known, through N-body simulations, consolidated by observations, it is interesting to test a toy model, in a semi-analytical way, including:

- star formation, with a combination of a quiescent rate, proportional to the gas density, in a time scale of 3 Gyr, and a bar-driven contribution, with a threshold ($Q < 1$) and a rate equal to $(1-Q)/t_*$, with $t_* = \beta t_{vis}$.
- radial flows: when a bar is formed, gravity torques produce gas inflow, therefore with a threshold $Q < 1$ also, and rate $(1-Q)/t_{vis}$, with $t_{vis} \sim \frac{1}{\Omega} (\frac{M_{tot}}{M_d})^2$. There is also a radial flow of stars, with efficiency $s_{eff} = 0.2$.
- bulge formation: the inflowing gas (and stars) are assumed to form the bulge through star-formation and vertical resonances
- death of bars: when $Q > 1$ (central concentrations, lack of gas and self-gravitating disk)
- gas infall: possibility of a continuous small infall or a periodically substantial one (from companions).

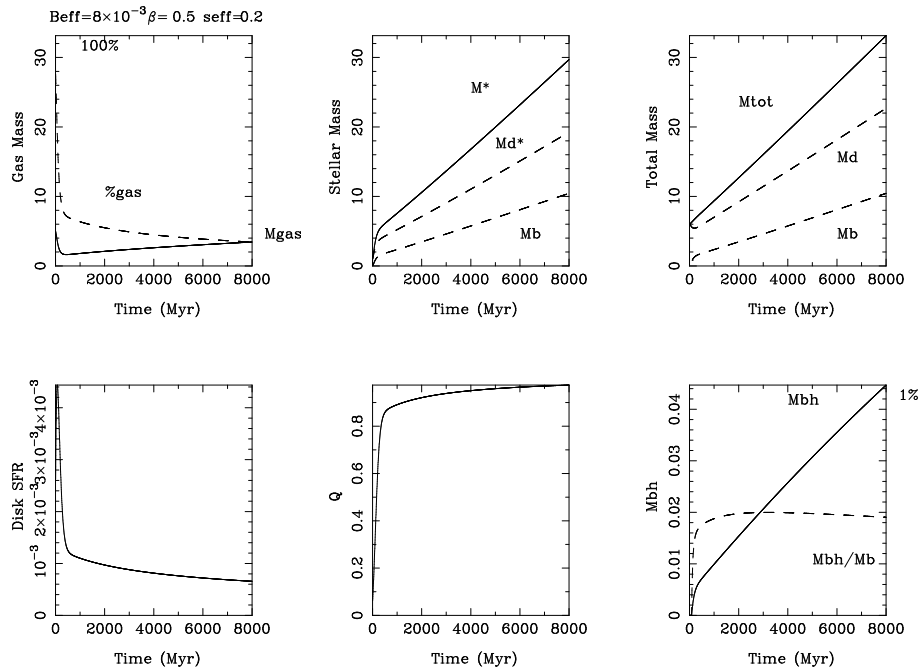


Figure 2. Continuous gas accretion model: **Top left** Full line: gas mass versus time; dash line: gas mass fraction. **Top middle** Full line: stellar mass; dash lines: disk stellar mass at top, and bottom bulge mass. **Top right** Full line: total mass; dash lines: total disk mass at top, and bottom bulge mass. **Bottom left** Disk star formation rate versus time. **Bottom middle** Toomre Q parameter. **Bottom right** Full line: mass of the central black hole, and dash line: mass ratio between the black hole and the bulge.

- black hole formation: a fixed fraction b_{eff} of the radial gas flow is taken to contribute to its formation, i.e. $dM_{bh}/dt = b_{eff}M_g(1 - Q)/t_{vis}$, with a threshold $Q < 1$.

Figures 2 and 3 display some results of the toy model. The most striking feature is the self-regulation of the stability parameter Q towards 1. Although the galaxy initially starts almost completely gaseous, the gas mass fraction soon stabilises to 10% of the total. Also the mass of the central concentration (or black hole) stabilises to a constant fraction of the bulge mass, as observed (Magorian et al. 1998).

5. Conclusion

Bars can be considered as one of the main driver of disk evolution. They produce gravity torques that drive matter inwards. They are gravitational instabilities that trigger star formation, with a time-scale comparable to that of radial gas flows ($t_* \sim t_{vis}$). Bar formation is self-regulated when gas is present: massive infall, due to the bar, can weaken the bar. This is accompanied by decoupling of

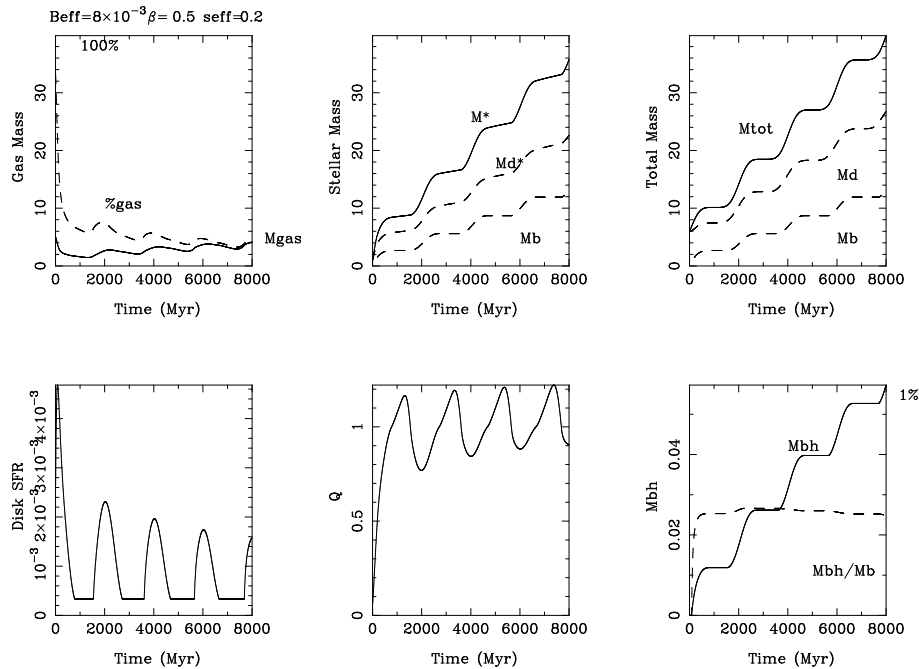


Figure 3. Same as figure 2 for a periodic gas accretion

a nuclear disk or second bar. On a Gyr time-scale, stellar bars thicken, through vertical resonances, and the subsequent destruction of the bar through gas flow leads to bulge formation. Bulges stabilise the disks and evolution is slower with time, following bulge growing. The formation of recurrent bars requires large gas infall.

Including these processes in a simple scenario, it is easy to reproduce the following features: tendency towards a nearly constant gas fraction (after a large decrease) and Q regulated around 1; the secular building of the bulge; the building and fueling of a central black hole. The latter is increasing rapidly, from a threshold in the bulge-to-disk mass ratio of $\sim 10\%$. Then the ratio of black hole mass to bulge mass tends to a constant, of 0.5% . To get the observed order of magnitude for this constant, only 0.8% of the gas flow towards the center has to be taken to fuel the nucleus.

References

- Athanassoula, E. 1992, MNRAS, 259, 345
- Barth A.J., Ho L.C., Filippenko A.V., Sargent W.L.W.:1995, AJ, 110, 1009
- Baum, S. A., Heckman, T. M., Van Breugel, W.: 1992, ApJ 389, 208
- Bureau, M., & Freeman, K.C. 1997, PASA, 14, 146
- Buta, R., & Combes F.: 1996, Fund. Cosmic Phys. 17, 95
- Combes, F., & Sanders, R.H. 1981, A&A, 96, 164
- Combes, F., Debbsch, F., Friedli, D., & Pfenniger, D. 1990, A&A, 233, 82
- Combes F.: 1994, in "Mass-transfer induced activity in galaxies" ed. I. Shlosman, Cambridge Univ. Press, p. 170

- Combes F.: 1996, in “Barred galaxies”, ASP Conf Series, Volume 91, ed. R. Buta, D. A. Crocker and B. G. Elmegreen, p.286
- Courteau S., de Jong R.S., Broeils A.H.:1996, ApJ, 457, L73
- Dahari, O.: 1984, AJ 89, 966
- Debattista, V.P., & Sellwood, J.A. 1998, ApJ, 493, L5
- Friedli, D., & Benz, W. 1993, A&A, 268, 65
- Friedli, D., & Martinet, L. 1993, A&A, 277, 27
- Fukuda H., Wada K., Habe A.: 1998, MNRAS 295, 463
- Hasan, H., & Norman, C.A. 1990, ApJ, 361, 69
- Hasan H., Pfenniger D., Norman C: 1993, ApJ 409, 91
- Heckman, T. M., Smith, E. P., Baum, S. A. et al.: 1986 ApJ 311, 526
- Heller, C.H., & Shlosman, I. 1996, ApJ, 471, 143
- Hockney, R. W., Brownrigg, D. R. K.: 1974, MNRAS 167, 351
- Hohl, F. 1971, ApJ, 168, 343
- Hutchings, J. B., Neff, S. G.: 1992, AJ 104, 1
- Hutchings, J. B., Morris, S. C.: 1995, AJ 109, 1541
- Ishizuki S., Kawabe R., Ishiguro M. et al.: 1990, Nature, 344, 224
- Kennicutt R., Roettiger, K. A., Keel, W. C. et al.: 1987, AJ 93, 1011
- Kennicutt R.: 1989, ApJ 344, 685
- Lin D.N.C., Pringle J.E.: 1987a, ApJ 320, L87; 1987b, MNRAS 225, 607
- Maciejewski, W., & Sparke L.S. 1997, ApJ, 484, L117
- Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
- Martin P., Roy J-R.: 1994, ApJ 424, 599
- Masset F., Tagger M.: 1997, A&A 322, 442
- Mcleod, K. K., Rieke, G. H.: 1995, ApJ 441, 96
- Merrifield, M.R., & Kuijken, K. 1995, MNRAS, 274, 933
- Miller, R. H., Prendergast, K. H., Quirk, W. J.: 1970 ApJ 161, 903
- Mirabel I.F., Dottori H., Lutz D.: 1992, A&A, 256, L19
- Moles, M., Marquez, I., Perez, E.: 1995, ApJ 438, 604
- Pfenniger, D., & Friedli, D. 1991, A&A, 252, 75
- Pfenniger, D., & Norman, C. 1990, ApJ, 363, 391
- Raha, N., Sellwood, J.A., James, R.A., & Kahn, F.D. 1991, Nat, 352, 411
- Regan, M. W., Mulchaey, J. S.: 1999 AJ 117, 2676
- Sakamoto K., et al.: 1999, ApJ in press (astro-ph/9906454)
- Sanders D.B., Soifer B.T., Elias J.H. et al.: 1988, ApJ, 325, 74
- Sellwood, J.A., 1981, A&A, 99, 36
- Sellwood, J.A., & Moore, E.M. 1999, ApJ, 510, 125
- Sellwood, J.A., & Wilkinson, A. 1993, Rep. Prog. Phys., 56, 173
- Shlosman, I., Frank, J., & Begelman, M.C. 1989, Nat, 338, 45
- Simkin S.M., Su H.J., Schwarz M.P.: 1980, ApJ, 237, 404
- Sprayberry, D., Impey, C. D., Bothun, G. D., Irwin, M.: 1995, AJ 109, 558
- Toomre, A., 1964, ApJ, 139, 1217
- Toomre A.: 1981, in “The structure and evolution of normal galaxies” NATO/ASI, Cambridge University Press, p. 111-136
- Tremaine S., Ostriker J.P.: 1999, MNRAS 306, 662